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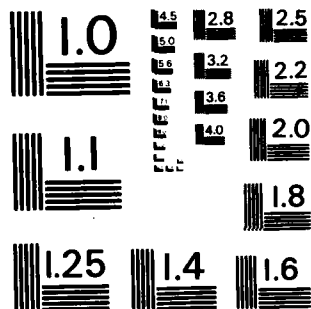
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AN EXPLORATORY STUDY INTO THE VARIOUS OBSERVED
COMPLEX FUNCTIONAL CHARACTERISTICS OF VISION
AND THEIR COMPATIBILITY WITH A UNIFIED SIMPLE

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SUMMARY

Over the last decade a great deal of experimentation has been reported on both the physiology of the eye and the human response to a variety of periodic and local structural patterns. Whilst such experimentation potentially assists modelling of visual performance, certain of the results have been interpreted as indicating various complexities and non-linearities in the human visual system. It is important for predictive modelling of complex situations to establish how far the visual system may be considered simple and linear. The present report surveys a wide range of physiological data and considers the implications on predictive modelling. It is considered that the majority of available data can be predicted by the use of a simple visual model provided that due allowance is made of local variations of quality factors in the retina.

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1. INTRODUCTION

Over the last decade a great deal of experimentation has been reported on both the physiology of the eye and the human response to a variety of periodic and local structural patterns. On the one hand parts of the physiology - such as measurements of the spread function of the refraction optics by retinal reflection (refs. 1 and 2), the measurement of the MTF of the retina (refs. 3 and 4) and studies of the responses of neural units such as bipolar and ganglion cells in lower animals (particularly refs. 5-11) - greatly assist in advanced modelling of visual performance. On the other hand experimentation on the response to complex patterns and periodic stimuli (e.g. refs. 12 - 24) shows very complex behaviour which is not readily reconciled with simple modelling of detection thresholds as carried out by Blackwell (ref. 25), Jones (ref. 26), Schade (ref. 27), Overington and Lavin (refs. 28 - 31) and others. Thus if we are to be able to develop predictive modelling for any but the simplest of situations it is necessary to attempt to relate these complex functional characteristics to some model, preferably simple.

As a result of previous studies it was believed that the edge gradient model of Overington and Lavin provided basic compatibility with both the physiological findings and the complex functional characteristics if due account was taken of the noise in the visual system together with the variations of eye quality and retinal structure as a function of image position. The present study of the detailed coupling of retinal neural units and of the possibility of re-interpretation of a broad range of complex visual functions in terms of a unified simple model was thus undertaken.

2. BIPOLARS AND GANGLION CELLS

2.1 PHYSIOLOGICAL DATA

In order to have confidence in a vision model which is to be applied to a complex target situation it is necessary that it be at least plausibly related to the known performance characteristics of the immediate post-retinal receptor neural elements. Now the main sequence of series processing in the retina (i.e. prior to the optic nerve) is from the receptors (rods and cones) to the bipolars and thence to the ganglion cells and the optic nerve (the input to the brain). It has been fairly thoroughly established by a variety of work on lower animals that bipolars have a behaviour which may be characterised as a central summative area with an annular surround area which inhibits the central area as shown schematically in fig.1 (e.g. refs. 5 and 6). It has equally been shown that some of the ganglion cells exhibit similar behaviour. However, there have been shown to be two distinct types of ganglion cell - the X and Y ganglions - where the X ganglions behave in a similar manner to the bipolars but the Y ganglions are primarily sensitive to temporal changes of retinal illuminance (refs. 8 - 11).

In all the foregoing studies an important fact is missing - the appropriate scale of the various summative and inhibitory areas as applied to man. Nevertheless, it is clear from some of the studies that in some lower animals the scale of summative and inhibitory areas of the bipolars are of the same order as the separation between receptors or receptor groups. Since such a scaling would appear to be optimal (and hence desirable from an evolutionary standpoint) it is considered reasonable to assume a similar optimal scaling in man in the absence of positive information. In a similar manner it is possible to infer the scale and relative roles of the two types of ganglion cells in man. For instance it is concluded in reference 9 that there are ganglion summative areas in the cat which vary from $\frac{1}{2}$ degree to several degrees for X ganglions, the smaller areas being predominantly near

2. Cont'd

foveal whilst the Y ganglion summative areas are larger. Also it is considered in the same reference that the X ganglions in the cat have a spatial frequency response characteristic similar to human cone vision. Coupling the above findings with knowledge that the cat has overall visual acuity which is lower than man's by a factor of 5 or 6 (ref.9) one may postulate that human cone vision is associated with ganglion cells of the X type, the summative areas of foveal ganglions being probably of the order of 5 or 6 minutes of arc. At the same time we may tentatively ignore the Y ganglions for photopic study of static stimuli.

Drawing together the information discussed in the previous paragraph we see that the bipolars appear to provide, in effect, some form of differentiation of the retinal illuminance structure with implied enhancement of sensitivity to corners and sharp curves (known to be an important facet of vision - e.g. Attneave, ref. 32). Available physiological data do not appear to permit absolute specification of the differential function, which may be simple or effectively 2nd differencing, dependent on the details of the dendritic coupling at the bipolars. Since simple differentiation best fits known blur threshold data this has been assumed to be the practical result of bipolar connections.

Subsequent to the bipolars the ganglion cells appear to provide a local integration of difference data. However, at threshold it may be argued that if the bipolars at the maximum gradient region of the retinal image are just responding, those at regions of significantly lower gradient are sub-threshold for bipolar response. Hence for sharp contours the composite effect of bipolars and ganglions is likely to be one of first differentiation to a first approximation (as found to provide a very good modelling of detection of simple objects by Overington and Lavin - refs. 28, 30 and 31).

The form and function of the inhibitory surround of the X ganglions remains to be explained. Now it has been found that this inhibitory surround can be of several degrees in extent, but that it is only in clear evidence with large differential illuminances (of the order of 1 or more log units). It is thus suggested that this form of inhibition is in effect a mechanism of adaptation to local areas of strong contrast and that for relatively low contrast or plain backgrounds it is not a significant factor in threshold modelling. Some confirmation of this view will be provided by the modelling of 'receptive field' data in Section 6.

2.2 PRELIMINARY CONSIDERATIONS OF IMPLICATIONS ON THRESHOLD MODELLING

Whilst simple 1st difference modelling has been shown adequate for prediction of detection thresholds for simple and sharp edged stimuli (refs. 28 - 31) it is imperative for modelling of complex stimulus patterns that due account be taken of the interactions of the object structure and the retinal mosaic, with the attendant spatial noise introduced. Now the response characteristics of various neural elements have been measured by Werblin and Dowling (e.g. refs. 5, 6 and 7) and found to have a characteristic response as illustrated in fig.2. Such response characteristics are common in general form to many familiar physical energy conversion units - photographic film, electronic valves, transistors, etc. - and imply that at each stage of neural processing there is a characteristic response which, to a first approximation (shown dotted in fig.2), may be stated as

$$R = a(S - b) - (1)$$

where R is the response,
S is the signal level (in appropriate units),
a is the incremental response to an incremental signal
(i.e. gain or gamma of the element),

and b is the threshold signal required to result in a 'significant' response.

Thus the ganglion response may be stated as

$$R_G = a_G (S_G - b_G) \quad - \quad (2)$$

Where the suffixes refer to ganglion properties.

But S_G is the local summation of a number of bipolar responses viewed in a spatial noise situation.

$$\text{Hence } S_G = \sum_{i=1}^i R_{Bi} \quad - \quad (3)$$

$$\text{where } R_B = a_B (S_B - b_B + \delta N_B) \quad (4)$$

δN_B being the spatial noise at the bipolar. Now assuming the noise to be random, and assuming a single glimpse threshold situation to be such that the ganglion response required for detection is minimal and related to the number of ganglion signals, the threshold level of ganglion signal will be related to the probabilistic sum of components from bipolars within its summation area,

$$\text{viz } S_G = \sum_i p_{Bi} R_{Bi} \quad - \quad (5)$$

Where p_{Bi} is the relative probability of an individual bipolar signal yielding a minimal bipolar response. Coupling this concept with the concept that a minimal ganglion response - being the input to the optic nerve at threshold - will permit $n(n-1/2)$ signal comparisons the brain yields the B.A.C. vision model with an additional facility for handling stimulus structure.

The above is obviously only the skeleton of an advanced threshold model. Further refinement must be the subject of subsequent studies. Also it takes no serious account of a number of complex behavioural characteristics of vision implied by recent literature. It is important that we know, before pursuing what is essentially a simple modelling, whether complex stimulus structure can plausibly be handled in a simple fashion. The remainder of the report seeks to show that it is reasonable to explain the majority of complex performance functions in terms of a simple, linear model.

3. CONTRAST SENSITIVITY FUNCTIONS

It was shown in the 2nd Visual Studies Contract (refs. 28 and 33) that the BAC vision hypothesis was capable of predicting the broad shape of the early contrast sensitivity functions of Campbell and Co-workers (refs. 2 and 34). It was also shown at that time that the form of the curve - a composite of a retinal MTF and a discrete sampling function due to the local receptor spacing - was relatively insensitive to receptor spacing and integration area up to a maximum separation of 1 minute of arc but that for spacings greater than this it became noisy. Sample curves for the central fovea with a 'like' receptor spacing of 0.7 mins of arc are shown in fig. 3. Now recent work by Graham and Nachmias (ref. 16) and by Sachs et al (ref. 35) using complex gratings consisting of two superposed

sinusoidal gratings has shown conclusively that the eye behaves, under their experimental conditions, as if it processes spatial information through several parallel band-pass filters. This is particularly in evidence in Graham and Nachmias' work where two superimposed gratings of relative frequencies f and $3f$ yield a threshold almost entirely dependent on whichever is the stronger of the two grating stimuli and independent of whether the two are in or out of phase. At the same time other workers have found that the form of the contrast sensitivity function is dependent on the size of the test field (e.g. Campbell and Robson, ref. 12, Watanabe et al, ref. 36 and Hoekstra et al, ref. 13). In particular Hoekstra et al suggest that the low frequency fall-off of the contrast sensitivity function is due to an insufficient number of presented cycles and suggest that a 'corrected' function should become constant for spatial frequencies less than about 10 c/deg.

3.1 PARALLEL PROCESSING AS A RETINAL EFFECT

For modelling of threshold response to complex local structure it is highly important to know the form of the contrast sensitivity function at a local region of the retina, whether or not parallel processing really exists for data received in a local region and, if it does, by how many separate channels. It would obviously simplify modelling if the apparent parallel processing could be explained as an artifact of presentation conditions. Now it is our belief that this is possible and that virtually all of the foregoing family of contrast sensitivity functions are predictable from the retinal image quality and retinal structure, the multi-channel processing itself being a retinal effect. As stated earlier, if with the known foveal retinal image quality the receptor spacing (or receptive field sampling) increases to greater than about 1 min. of arc the resultant composite contrast sensitivity function is noisy. But when spatial patterns subtend several degrees at the eye parts of the patterns are detected by receptors spaced by considerably more than 1 min. of arc (e.g. ref. 37). Now our previous work has shown a very good prediction of peripheral thresholds for photopic vision out to at least 15° from the fovea by assuming the threshold to be dependent on receptor spacing, provided that retinal image quality also falls off roughly in proportion to receptor spacing. Such an assumption of progressive fall-off of optical quality at a similar rate to coarsening of the receptor matrix obviates the noisiness of contrast sensitivity functions as the receptor spacing increases beyond 1 min. of arc and leads to a set of contrast sensitivity functions for various annular regions of the retina centred on the fovea as shown in fig. 4. Each of these is the combination of a local MTF curve and a sampling function of the form $\sin 2\pi f x$, where f is the spatial frequency considered and x is the local receptor spacing. If now the situation of increasing patterned field is considered one must assume that the composite contrast sensitivity function is the envelope containing all elementary functions possible within that field. This results in a set of functions as in fig. 5 which show strong similarity to the experimental curves of Hoekstra et al (shown dotted) except for the rate of fall-off of performance at very low frequencies. It is thus suggested that a major part of the low frequency limit of contrast sensitivity function is due to sampling, the rest being due to limited stimulus 'size'.

Our explanation is preferred to Hoekstra's since, in terms of contour length, even one cycle in general constitutes a 'large' target (i.e. equivalent to a disc of 20 or 30 mins diameter at least - c.f. Blackwell, ref. 38) and hence there should not be major fall-off with several cycles present.

3.2 PERIPHERAL CONTRAST SENSITIVITY

Very little data appear to be available on peripheral contrast sensitivity. Following on from the assumptions that the 'tuned' channels' in human vision are radially spaced from the foveal and are due to retinal quality plus sampling, one can predict an overall response function at any distance from

the Fovea. Now there does exist one set of data on peripheral contrast sensitivity that of Daitsch and Green for 12° from the fovea (ref. 15). These data, shown in fig. 6, show the normal form of band pass function at high retinal illuminance with an apparent change of shape as retinal illuminance falls. If one of the high illuminance functions is plotted on the same scale as a predicted function from BAC vision modelling for a 12° eccentricity with a low frequency cut as found by Hoekstra et al then the result is as shown in fig. 7, this being considered in very close agreement.

If now the total situation is considered as light level is reduced there are several mechanism which must be considered. Firstly, at high frequencies, where the effective stimulus contributions along maximum gradient regions of the retinal image are very large, δ in the vision model will control threshold. But δ is a function of quantum noise and hence retinal illuminance (ref. 31). Therefore the whole curve will be displaced bodily downwards on the contrast sensitivity axis. At lower frequencies, where the number of stimulus components in the field is not approaching infinity the increased level of noise will result in a widening tolerance band for generation of significant stimulus components, resulting in an enhancement of the low frequency response progressively. However, there will eventually come a limit where this increased contribution again causes δ to predominate and subsequently the full effect of reduced performance due to noise on δ will again start to be felt. The total result of all this is a probable set of curves (schematic) as shown in Fig. 8. It will be seen that these bear a strong resemblance to the experimental results of Daitsch and Green in Fig. 6.

Limited circumstantial confirmation for this simple explanation of log shift of the contrast sensitivity functions dependent on the local receptor spacing is to be found in the work of Ohzu and Enoch (ref. 4). They have measured the MTF of freshly excised isolated retinae and found a suspicion of considerable degradation away from the fovea. It is true that their very limited data are contaminated by a known degradation due to ageing in the dying retina. Nevertheless their presented data, which include ageing effects, are grossly inferior to the performance predicted from the $(\theta + 1)$ law used by Overington and Lavin to describe the receptor distribution (ref. 30) and could well include this. Their footnote implies that they expect some considerable (unspecified) degradation due to thickening of the membranes and increase in size of receptor cells away from the fovea. This explanation has been confirmed by recent personal communication with Enoch but no further studies on excised peripheral retinae have been undertaken by him.

It should also be noted that the known increase in size of retinal receptor cells away from the fovea, together with the progressive grouping of cells in the periphery, itself leads to a narrowing $\sin x/x$ or Bessel function in frequency space which, when combined with the narrowing sine function due to increasing sampling increments, leads to a retinal/neural response in its simplest form as shown in fig. 9, this function being to a base scale almost directly proportional to the reciprocal of receptor spacing. Such a function could be argued to be a better fit to the high luminance Daitsch and Green data for 10° peripheral than the function in fig. 7 which assumes degradation of the optical image as well.

4. THRESHOLDS FOR COMPLEX PERIODIC PATTERNS

4.1 THRESHOLDS FOR OTHER THAN SINE BARS

It has been shown that the contrast sensitivity function is dependent on the presented field and it has been argued that this is due to the effective 'tuning' of the said function as the image moves away from the centre of the fovea. What happens when other than sine wave bar patterns are presented? Well, Campbell and Robson (ref. 12) showed that the threshold trends for

square bar patterns and rectangular bar patterns were as if only the fundamental was detected for high spatial frequencies (above say 3 cycles/degree for square bar patterns or above about 10 cycles/degree for rectangular bar patterns with an 0.1 duty cycle). Fig. 10 shows their comparative results for square and sine bars. At high frequencies the square bar threshold is approximately 1.27 times better than the sine bar threshold. Now the Fourier series representing a sine wave is

$$F(x) = 4/\pi \left[\sin \omega x + \frac{1}{3} \sin 3\omega x + \frac{1}{5} \sin 5\omega x + \dots \right] \quad (6)$$

Thus the fundamental amplitude is $4/\pi$ (≈ 1.27) compared with the amplitude of the square wave. Hence at high frequencies, where the higher harmonics would tend to be attenuated due to the MTF of the eye's refraction optics, etc., the threshold trend is as expected. At low frequencies, however, Campbell shows that the trend is out of keeping with a simple peak detector mechanism. Equally it can readily be shown that it is out of keeping with a simple maximum slope detector without due consideration of noise. However, let us now consider noisy signal processing (as opposed to a noisy signal). Such processing may be considered as a signal detection problem in the presence of essentially white noise. Now if we consider that amplitude in the space domain has a normal probability associated with it then the frequency spectrum must equally have a normal probability associated with it since the Fourier transform of a gaussian is a gaussian.

Then if one computes the sampled strengths of various frequency components of the signal, each of these is going to produce a probabilistic response dependent on its strength relative to that of the strongest component. Now the noise free signal for a square wave based on sampled 1st differencing would be

$$A(\omega) = 4/\pi \left[m_{\omega} \sin \omega \delta x + m_{3\omega} \frac{1}{3} \sin 3\omega \delta x + m_{5\omega} \frac{1}{5} \sin 5\omega \delta x + \dots \right] \quad (7)$$

where m_{ω} , $m_{3\omega}$, etc., are the image modulation as sampled for spatial frequencies ω/π , $3\omega/\pi$, etc., and δx is the sampling increment. But in general m_{ω} is greater than $m_{3\omega}$ etc., and for low frequencies (where $\omega \delta x \ll \pi/2$) $\sin \omega \delta x \gg \sin 3\omega \delta x/3 \gg \sin 5\omega \delta x/5$. Then the total response for low frequencies will be nearly equal to

$$4/\pi \sin \omega \delta x [m_{\omega} + m_{3\omega} + m_{5\omega} + \dots] \quad (8)$$

where the series becomes modified only at frequencies where $\omega \delta x$ approaches or exceeds $\pi/2$. If now the individual components of this simplified approximate series are taken as fractions of the maximum (m_{ω} in the case of the square wave) and if a given noise level is selected for the processing networks as a function of mean threshold response, we may assign a probability to each component $m_{n\omega}/m_{\omega}$ depending on its fractional value. Summing the probabilities and multiplying by $4/\pi$ should then yield the improvement of thresholds over a sine bar pattern at frequency ω/π .

Mathematically the above is stating that

$$(T_{\omega})_{\text{square}} = (T_{\omega})_{\text{sine}} \times 4/\pi \left[\Phi_{m_{\omega}} + \Phi_{m_{3\omega}} + \Phi_{m_{5\omega}} + \dots \right] \quad (9)$$

Where

$$\Phi_{m_{n\omega}} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2} z^2\right) dz,$$

this being the normal probability integral where in our case

$$z = \log \left[\frac{m_{n\omega} \sin n\omega \delta x}{n m_{\omega} \sin \omega \delta x} \right] / \sigma \quad \text{in general or} \quad z \approx \log [m_{n\omega}/m_{\omega}] / \sigma$$

for significant components at low frequencies, σ^2 being the assumed noise variance in the processing networks. The above reasoning leads to predictions of the square wave/sine wave response ratio for a 2° square viewing field as used by Campbell and Robson as shown in fig. 11. A comparison at those curves

with experimental ratios in fig. 10 will show that a noise variance such that $\sigma \approx 0.2C_M$ gives a good agreement. Using this same variance yields the comparative contrast sensitivity curves for sine and square waves shown in fig. 12.

Naturally there must be minor discrepancies in the use of the foregoing due to uncertainties in the magnitude of various contributory factors to the overall sampled image quality as a function of retinal position, but the overall predictions are considered good. Similar reasoning could, of course, be applied to the rectangular bar thresholds of Campbell and Robson but here the presence of many significant harmonics makes rigorous computation laborious.

4.2 SUPERPOSITION OF TWO SINE BAR PATTERNS

Armed with an approach to complex pattern threshold prediction it is time to look in greater depth at other experimental studies recently pursued to investigate 'parallel processing'. Graham and Nachmias (ref. 16), as stated earlier, have carried out studies where they presented composites of two sinusoidal patterns, one of 3 times the frequency of the other. When the thresholds for each pattern individually were found and then the two patterns were presented with modulations either proportional to their relative thresholds or with a factor of 2.1 to their respective thresholds it was found that the threshold of the composite was close to that of the stronger of the two when presented individually or to that of either when presented together. Furthermore the compound thresholds were not significantly dependent on whether the contributing patterns were in or out of phase. Graham and Nachmias took this as strong evidence of parallel processing by tuned circuits.

If, now, one considers the noisy processing of sampled first difference information in conjunction with the 'tuning' enforced by the variation of sampling as a function of retinal image position it becomes imperative that the sort of results observed by Graham and Nachmias are obtained over the range of frequencies within which differential performance is possible at different retinal positions. With the field at pattern presentation used by Graham and Nachmias this amounts to pairs of frequencies of ratio 3:1 within the approximate range 1 to 15 cycles/degree (almost the extent of frequencies studied by them). Outside this frequency band - where no data are known to exist (could it be that data has been suppressed because it confused the issue?) - one might expect the thresholds for composite patterns to tend more closely to that expected from simple summation. Equally, if the frequency ratio is less than 3:1 the band at 'separation' might be expected to narrow and eventually, for small ratios, one would expect straight summation. This general trend of behaviour is close to that found by Burton (see section 4.4) and is also broadly in keeping with the findings of Sachs et al (ref. 35) in their studies of the probability functions for complex patterns comprising variable mixtures of two incoherently related sine bar patterns.

4.3 RECOGNITION OF FORM OF BAR PATTERNS

Campbell and Robson (ref. 12) have found that the threshold for recognition of the form of a bar pattern (square, sinusoid, triangular, missing fundamental, etc.) appears to be defined by the lowest significant harmonic reaching its own threshold. That this should be so is directly predicted from the foregoing sections since it is necessary for the sampled components of the important harmonics to reach the noise threshold individually in order for them to be perceived with 50% probability.

4.4 'NON-LINEAR' VISUAL PROCESSES

Burton (ref. 14) has recently presented 'evidence' that a non-linear process occurs early in the visual system. This 'evidence' takes the form of an illustration that if two incoherently related interference fringe patterns are overlaid on the retina, the frequencies being close to each other or close to a ratio of 2:1, even when the individual frequencies cannot be resolved the 'beat' frequency can still be observed. Since the input can be specified as

$$L(x) = A(1 + a \cos 2\pi f x + b \cos 2\pi f' x) \quad - (10)$$

he argues that with any linear system no other frequencies than f or f' can be extracted and hence one requires a non-linearity to observe the 'beat' when response to f and f' is sub-threshold. I consider that such observations do not imply a non-linearity. The composite waveform for such an input will be as shown in fig. 13. This is a typical amplitude modulated carrier wave situation where the two input frequencies relevant are not f and f' but $(f+f')/2$ (the carrier) and $(f-f')/2$ (the 'beat' frequency). This wave may be described, as an alternative to Burton's equation, as

$$L(x) = A \left[1 + (a+b) \cos \frac{(\omega+\omega')x}{2} - (a-b) \sin \frac{(\omega-\omega')x}{2} \right] \quad - (11)$$

where $\omega = 2\pi f$, $\omega' = 2\pi f'$, $\omega = \frac{(\omega+\omega')}{2} + \frac{(\omega-\omega')}{2}$ and $\omega' = \frac{(\omega+\omega')}{2} - \frac{(\omega-\omega')}{2}$.

This in turn yields the amplitude modulation as from $(a-b)$ to $(a+b)$ with a carrier wave phase change of π from peak to trough of amplitude modulation. The visual system now has the task of detecting either the carrier wave (at mean amplitude a) or the side band of the 'beat' frequency (at amplitude b). With a random sampling system operating on discrete sampling intervals which are such that they are of the same order as the period of the carrier wave it is unlikely that the carrier can be distinguished from noise. However, the average signals along a contour of the beat envelope must average out to yield a finite signal, if only as a strengthening and weakening of local noise in bands.

Looked at mathematically the threshold for the 'beats' should be defined by the appropriate part of the contrast sensitivity curve (as found very markedly by Burton). Pursuing the argument further one would expect that for receptors with finite sampling area the input image produced by the individual interference fringes would itself be attenuated by local integration as a $\frac{\sin x}{x}$ Function of Frequency (or more strictly a $J_1(x)/x$ Bessel Function). With approximately known receptor sizes this $J_1(x)/x$ function would be such as to cause severe attenuation of fringes with frequencies in excess of about 1 cycle/min, finally cutting off completely at around 1.5 cycles/min. Under such circumstances, as again found by Burton, there would be no modulation left in the carrier wave, and hence no possibility of sampling the 'beat'.

The foregoing has dealt with Burton's findings for $f \approx f'$. Similar (although more complex) 'beat' and carrier functions can be derived for $f \approx 2f'$ and $f \approx 3f'$. In the case of $f \approx 2f'$ a fairly strong 'beat' modulation is to be expected, with thresholds again obeying the trends of the contrast sensitivity functions as found by Burton. With $f \approx 3f'$, although the 'beats' are present, their amplitude is very much lower than in the previous cases due to the properties of the 3rd harmonic phase functions. Thus it is not surprising that "no 'beats' could be observed".

5. ADAPTATION TO SPATIAL PATTERNS

It has been found by several workers that the threshold performance against spatial bar patterns is affected by a previous time history of viewing suprathreshold bar patterns. For instance Gilinsky (ref. 39) has found that exposure to horizontal bars will enhance thresholds for horizontal bars and degrade them for vertical bars. Pre-exposure to vertical bars produces the reverse effect. Equally Tolhurst (ref. 18) has found that pre-exposure to bar patterns of a specific frequency will inhibit subsequent threshold performance for that frequency to an extent dependent on the contrast of the adapting bars. To a lesser extent the 3rd harmonic of a square wave has an adapting influence. Yet again Campbell et al (ref. 40) have shown that pre-exposure to a given frequency affects thresholds to a significant extent for frequencies within an octave either side of the adapting frequencies. Finally Stromeyer and Julesz (ref. 17) have shown that one dimensional noise within an octave of a displayed bar pattern frequency will have an effect on its detectability. Since all the above are concerned with what amounts to suprathreshold structure situations, and since the patterns were purposely scanned randomly by some observers to eliminate any chance of an after-image, it must be concluded that they are not a function only of single glimpse retinal effects and hence cannot be modelled fully by our vision model. However, whilst it could be that the implied 'learnt' bias in sensitivity to particular patterns is of importance in recognition situations it could equally be argued that it only provides useful evidence of the ability of the visual system to enhance and suppress various structures preferentially. It seems to me highly likely that such enhancement and suppression is related to detail form and not to the spatial frequency content of the scene other than in situations where the background may be adequately considered to be a form of random noise. Indeed such a conclusion must be reached to some extent from Tolhurst's findings of 'inhibitory interactions' between the adaption effect of fundamental and 3rd harmonics and the total suppression of adaptation effects of 5th and higher harmonics in square waves. Thus we may conclude tentatively that spatial adaptation is not a property of vision which can be modelled by the BAC model, but that, whatever the details of the effects, they are separable from retinal threshold effects..

6. THRESHOLD DISTORTION BY LOCAL STRUCTURE FOR ISOLATED OBJECTS

Thus far our considerations of the complex visual functions have been restricted to various forms of periodic pattern. Such situations, whilst being of value in illustrating some facets of total behaviour for a linear system, do not necessarily permit a full appreciation of what happens when one must detect isolated objects in the presence of noise. Consequently, a wide range of studies have been carried out in recent years to determine effects of local structure on thresholds for isolated objects. Such studies, although presented as a variety of manifestations of spatial inhibition, may be (and should be, it is considered by the author), separated into two groups, those concerned with near threshold or sub-threshold local background structure and those concerned with high contrast local structure.

6.1 Effects of Sub-Threshold and Near Threshold Structure

It is considered that the entire range of threshold distortions due to sub-threshold and near threshold structure may be plausibly explained very simply in terms of the sampled retinal image. Almost without exception the experimenters reporting on this form of study appear to ignore completely the fact that the image sampled at the retina is very considerably degraded by optical and retinal quality effects. When these are allowed for, and the resultant sampled 1st difference signals are considered, the experimental findings are no longer any great surprise.

For example, Fiorentini and Maffei (ref 21) have studied the effect on foveal threshold of a flash-presented, small, disc stimulus by the presence of various sub-threshold centred annuli of constant area but differing mean radius (i.e. varying from small radius, thick walled to large radius, thin walled). Their main results are illustrated in Fig 14. It will be seen that the main trend is for there to be an enhancement of threshold over the plain field situation for the annuli of small radius, a pronounced degradation of threshold for annuli of intermediate radius and a recovery to the plain field situation for annuli of very large radius. Fig 15 illustrates the cross sections of various annuli and of the flash stimulus, together with the approximate foveal retinal images which may be expected. When the images of the disc and the annulus are superimposed it will be seen that the composite result is very dependent on the size of the annulus. For a small annulus (a) the edge gradient of the disc is enhanced, thus predicting an improvement of threshold from the plain field situation. Alternatively, for the intermediate annulus radius (b) the disc image has a tendency to 'sink' into the centre of the annulus. Bearing in mind that it is the disc which is to be detected it is only the edge gradients associated with the disc which should be important and it will be seen that these are considerably softened compared with the plain field situation. Hence, a degradation of threshold is predicted in this area. Finally, for large annuli, where the central valley of the annulus image is larger than the significant image of the disc, the threshold should be unaffected by the presence of the annulus. All the above are seen to be in broad agreement with experimental results.

Detail modelling of the threshold trends is, however, dependent on the exact post-retinal functions outlined in Section 2 and hence must await more detailed modelling at some later time.

A second example of the effects of sub-threshold structure is to be found in the work of Kulikowski (ref 23). Here the threshold for a single bar target was studied when it was presented on a sub-threshold sinusoidal modulation of the field.

The bar was always presented parallel to the bars of the modulation, studies being carried out with modulation of 5c/degree and 20c/degree and with the bar presented either on the peak or trough of the modulation. It was found that for the 5c/degree modulation the bar threshold was enhanced when superimposed on the peak of the modulation and degraded when superimposed on the trough. On the other hand, for the 20c/degree modulation the threshold was largely unaffected by presence of the modulation. If we now consider the retinal imaging of the bar superimposed on the various modulations as illustrated in fig.16 it is immediately obvious that the super-position on the peak of a 5c/degree sine pattern enhances threshold (a), whilst super-position on the trough degrades threshold (b). Equally, it can be seen from (c) and (d) that, having allowed for the relative scales of retinal image of the sub-threshold sine pattern, the spread of the bar image is so great compared with a period of a 20c/degree pattern that the only major affect of the phase relationship is to change the positions of the gradients and not their magnitude.

As a result of these findings of Kulikowski the same author, in collaboration with King-Smith, carried out an extensive study on the threshold dependency of bar stimuli superimposed on a variety of local patterns - gratings, bars and edges (ref 41). From their results they postulated the existence of a variety of 'detectors' in the visual system sensitive to specific gratings, bar thicknesses and edges, thus extending the concepts of Campbell & Robson, Graham & Nachmias and others of the multichannel processing. However, once again it is believed that the experimental results can be largely predicted simply by considering the quality and interactions in the sampled retinal image.

For instance, Fig 17 shows Kulikowski and King-Smith's experimental results for threshold of a bar in the presence of two sub-threshold lines equally spaced either side of the test stimulus. The characteristic central peak with 'inhibitory' surround will be observed. If now we consider the retinal images of these complex presentations as in Fig 18 it will be seen that, as with Fiorentini & Maffei's annuli, the basic form of threshold trend may be anticipated. With +1min separation there is a massive enhancement, at +3mins separation there is a marginal effect (difficult to define), at +6 mins there is a major degradation and by inference, as the lines get even further apart there must be a gradual recovery.. Similar arguments can be applied to Kulikowski and King-Smith's results for various sub-threshold grating frequencies and for sub-threshold edges. However, once again the detailed modelling of trends relies on the details discussed in Section 2. It thus seems that, in direct contrast to Kulikowski and King-Smith's statement that their results show grating, line and edge detectors to be quite distinct from one another, it is possible that all their varied results may be predictable from the quality of the retinal image and an effective sampled first differentiating at the ganglion level. A point of interest in study of Kulikowski and King-Smith's paper is that they show ability to start with a contrast sensitivity form of function and predict from it such threshold functions as that shown in fig 17. This is of course a characteristic of a linear system, all that seems to be missing from

their analysis being the retinal origin of the contrast sensitivity function as proposed in earlier sections of this report.

It would, however, require a considerable amount of additional detailed modelling to be in a position to refute their claims of multichannel processing positivity.

6.2 Effects of High Contrast Structure

What is believed by the present author to be a completely separate spatial interaction effect to that discussed in Section 6.1 occurs when local regions of high contrast structure occur close to a target.

Typical of the form of local structure studied are a variable diameter, variable luminance circular patch of background superimposed on a flashing test stimulus and a low general background luminance such that the flashing stimulus is in the centre of the variable local background (See fig 19). The luminance of the flashing stimulus is first set at a fixed high level, usually some 1 to 2 log units above its threshold in the presence of the general background, and then the required level of local background luminance needed to reduce the flashing stimulus to threshold is established as a function of size. A typical set of results for foveal viewing are shown in fig 20 (from ref 20).

It will be seen that as local background area is increased so the required luminance is first reduced, suggesting constant energy being required, then levels off and finally, at large surround areas, increases again except at the lowest flashing stimulus luminance. The trend at small surround sizes is, of course, to be expected, since with very small surrounds they are imaged at the retina as unresolved points and hence will require a fixed amount of energy (or luminance inversely proportional to area) in order to produce a given effect on the test stimulus. The rest of the function, I believe, requires consideration of the receptor response functions of Werblin's (Fig 2 and ref 7) in conjunction with response functions of neural units as discussed in section 2.2 and general concepts of adaptation.

Fig 21 illustrates the retinal image profiles and the bipolar responses for cases of an unresolved local surround, an intermediate surround and a large surround. At (a) the flashing stimulus simply increases the height of the existing spread function without changing the shape. Thus the task becomes one of detecting an intermittent increase in peak bipolar response in the presence of noise - the constant energy situation. At (b) the local surround is partially resolved with the result that the peak differences due to the test stimulus no longer fall on the peaks of the bipolar response due to the local surround. The task now is that of detecting intermittent local differences adjacent to the steady peaks, which, as long as they are close together, implies a more difficult signal/noise situation, thus requiring a lower surround luminance to suppress the test stimulus than would otherwise be the case. This increase in difficulty will counterbalance a tendency for surround threshold to stabilise at moderate sizes and cause an effective broadening of the 'constant energy' region beyond that of the optical spread. This may be likened to the extension of Ricco's law to regions well beyond the true optical point source region for detection of single discs (ref 30). Finally, at (c) the test stimulus is entirely contained on the platform of vertical illuminance and hence one might expect bipolar peaks associated with it to be detected in their own rights.

This I believe to be the case - which should leave originally suprathreshold stimuli still suprathreshold whatever surround level is selected (i.e. a much steeper rise to curves in fig 20 than obtained!).

However, for situations where local adaptation can take place the receptor response curve of fig 2 will move bodily to the right.

Thus the increment threshold will increase in proportion to the shift of the curve and an effective constant situation will be reached for large surrounds which is controlled by the level of such luminance relative to the test stimulus.

The foregoing reasoning is believed to explain the results of fig 20 except for the lowest curve. Here, as with other observations showing no rise in threshold with large surround sizes under conditions near absolute threshold, the trends are assumed at present to be due to the fact that, in the limit, such approximations as that of fig 2 near the toe, in conjunction with random noise, are inadmissible.

Other data on 'receptive fields' presented by Enoch et al (ref 20) show the trough of the surround threshold function to be shifted to larger surround sizes both for foveal presentation of blurred stimuli and for peripheral presentations of the test and surround fields (e.g. fig 22). Such findings are in keeping with all the arguments and findings discussed in this report and serve to strengthen belief that the entire visual system can be considered as a parallel set of local series-processing channels, provided that due account is taken of local adaptation effects (possibly a simple exponential as first assumed by Mach and subsequently by Fry and others (ref 42)).

6.3 Scotopic Receptive Fields

Whilst not considered here since photopic vision is the visual process currently being modelled, it is perhaps worth passing comment that various experimenters have also studied receptive fields for scotopic vision, both for sub-threshold annuli (refs 24 and 43) and for local plateaux (refs 22 and 24). The findings in general were that the threshold exhibited similar trends to those in photopic conditions, but with much increased lateral dimensions. Although not part of the present exercise, it is interesting to note that the scaled-up threshold trends are to be expected from consideration of a scotopic function of the same form as the photopic but allowing for rod-grouping.

7. CONCLUSIONS

It has been shown that, by taking due account of the various known and implied properties of the human eye and associated neural networks, one can predict a wide range of apparently complex threshold trends whilst still assuming the visual process at any local point on the retina to be simple and linear. A broad indication has also been given of a probable way of modelling the response of the bipolar and ganglion cells in order to permit prediction of detection thresholds of degraded and complex stimuli. All such modelling, it would appear, may be essentially based on detection of first and second differences of retinal illuminance in a signal to noise situation with subsequent signal comparison at the brain.

It must be stressed that, at this stage, the concepts of a simple unified model of detection along the lines illustrated have only been shown to be plausible, and not proven. Confidence in the generality of such modelling can only be gained by repeated and varied application, together with progressive refinement.

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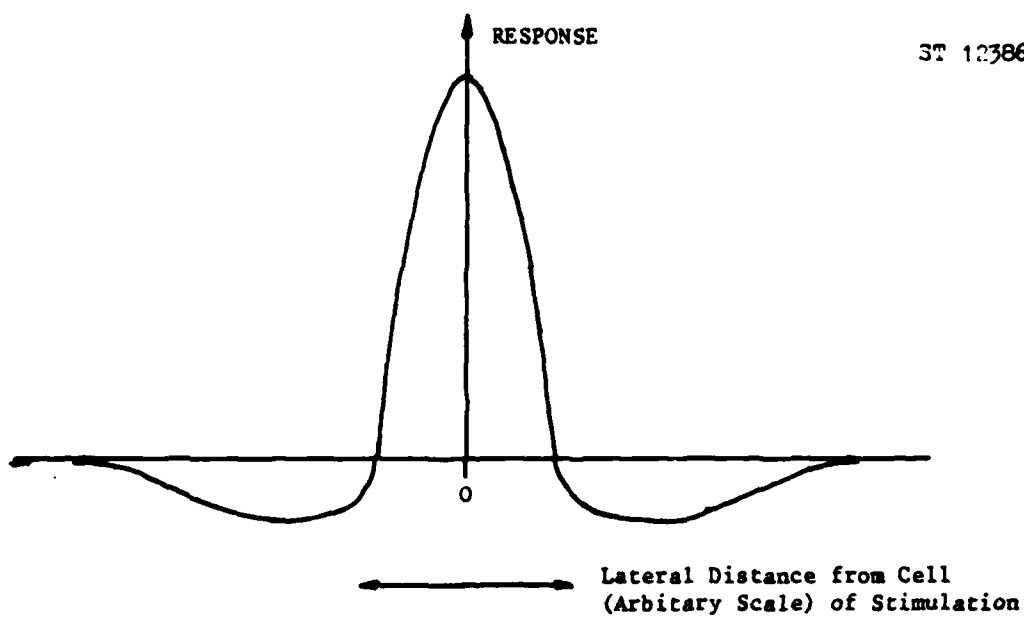


FIG.1 Stylised Representation of the Response Function of a Typical Neural Unit (Bipolar or Ganglion).

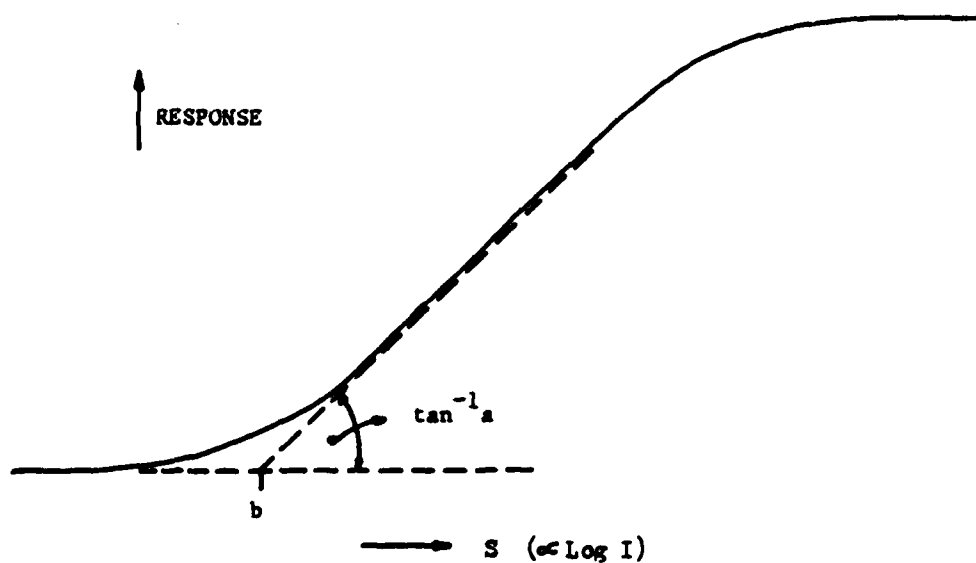


FIG.2 Typical Response Characteristic for Retinal Units.
I is the Intensity of the Signal.

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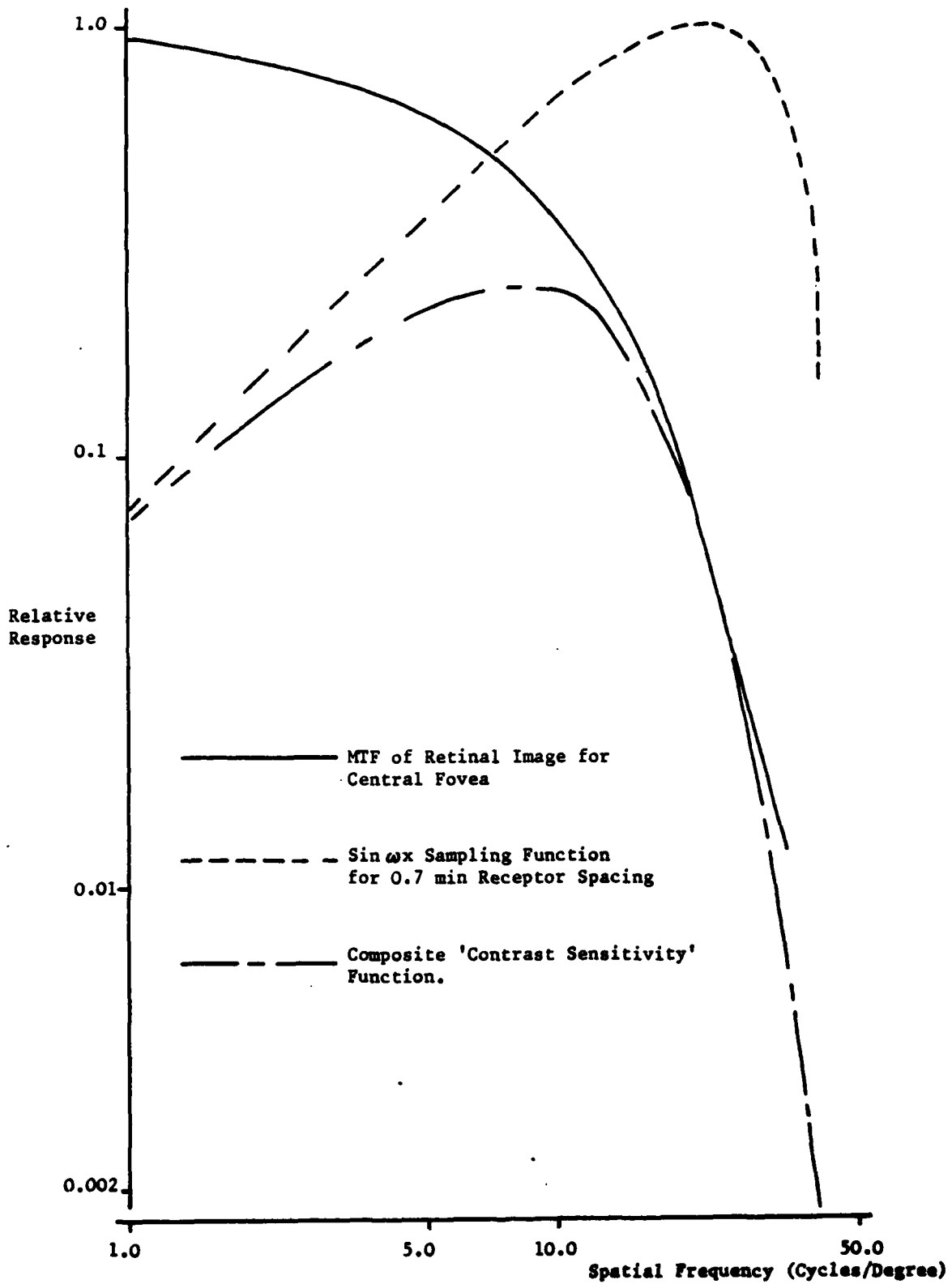


FIG.3 Frequency Response Functions for the Central Fovea

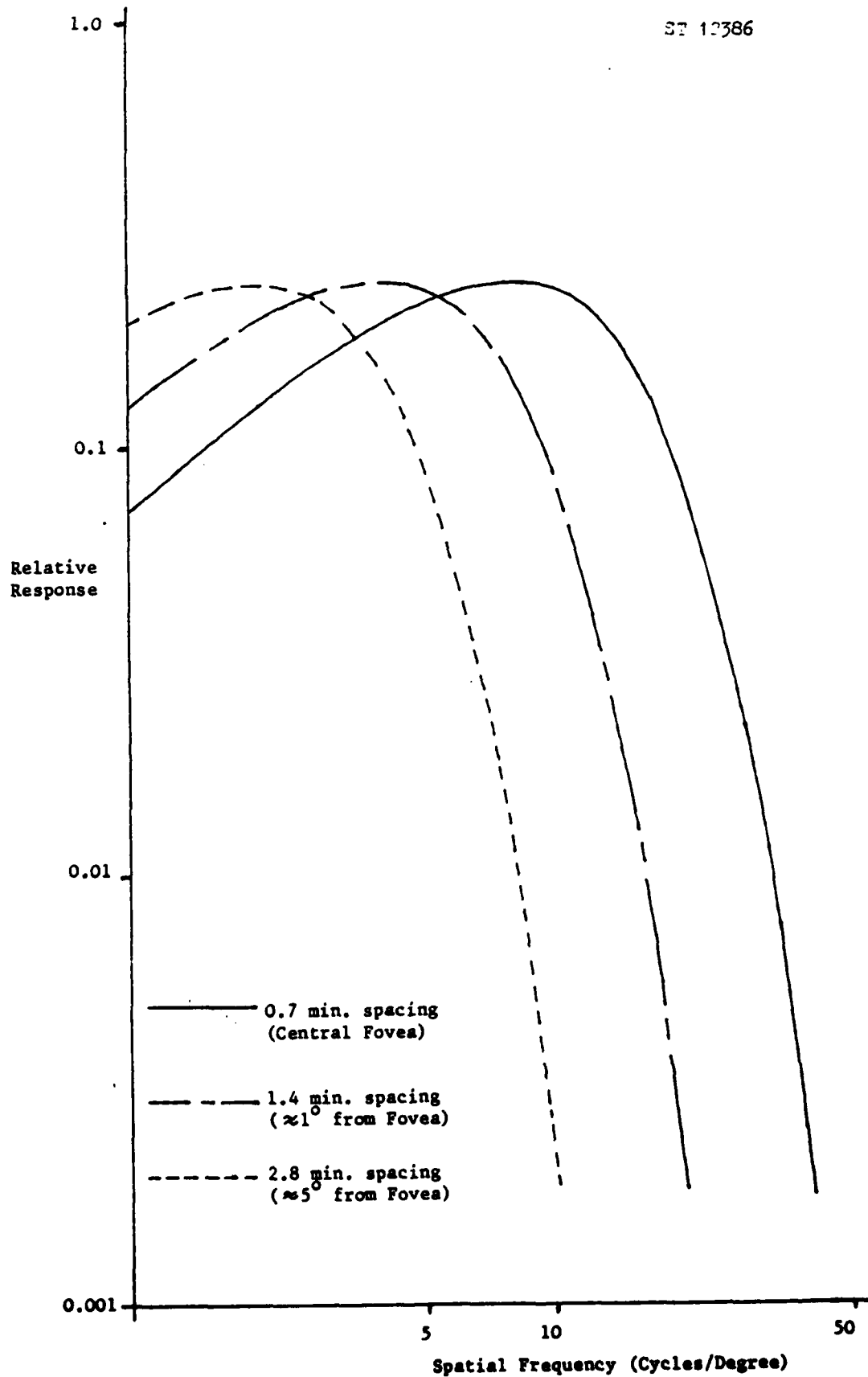


FIG.4 - Contrast Sensitivity as a Function of Local Receptor Spacing
(Assuming 'Matched' Optical Quality)

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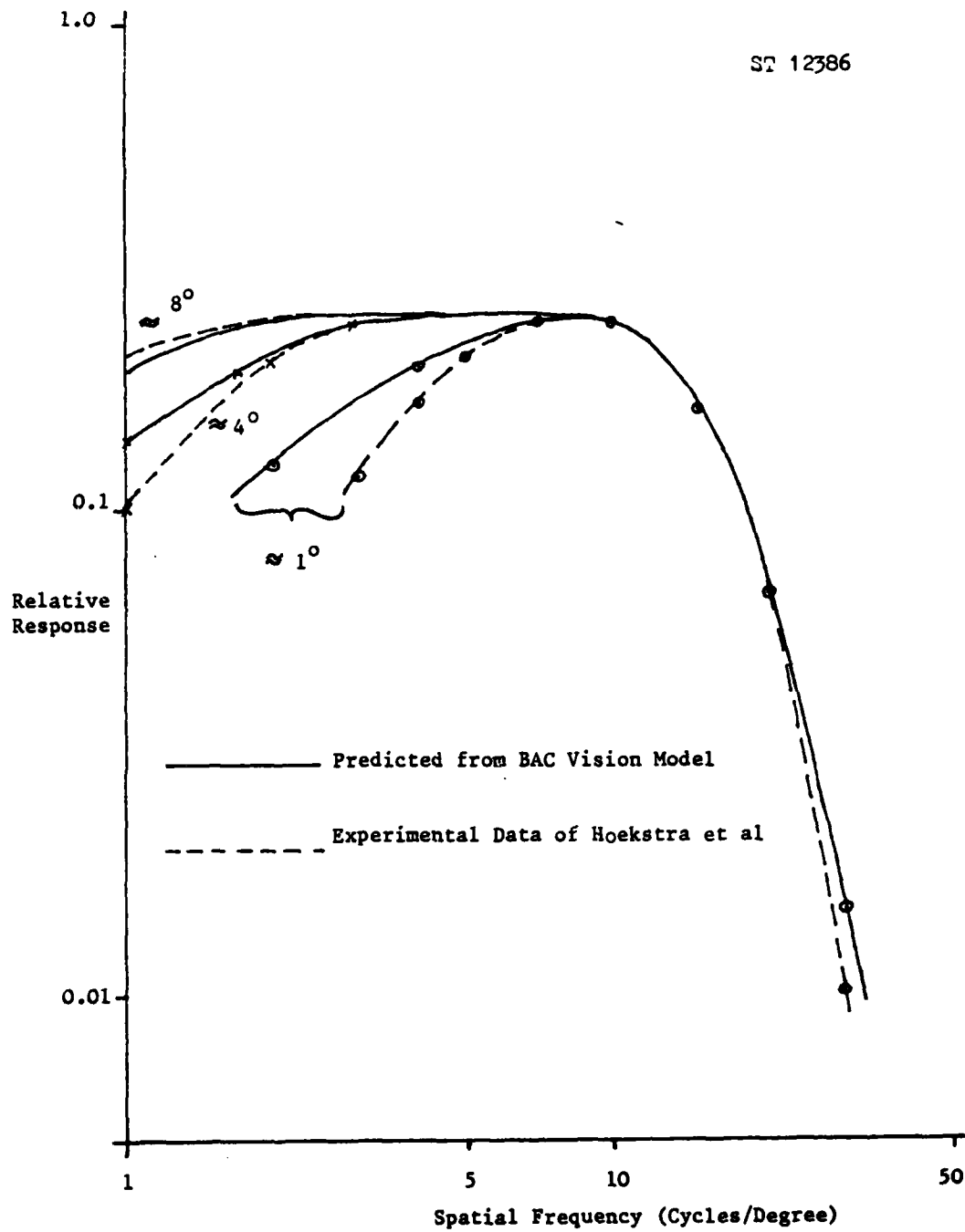


FIG.5 - Contrast Sensitivity as a function of Patterned Field Size

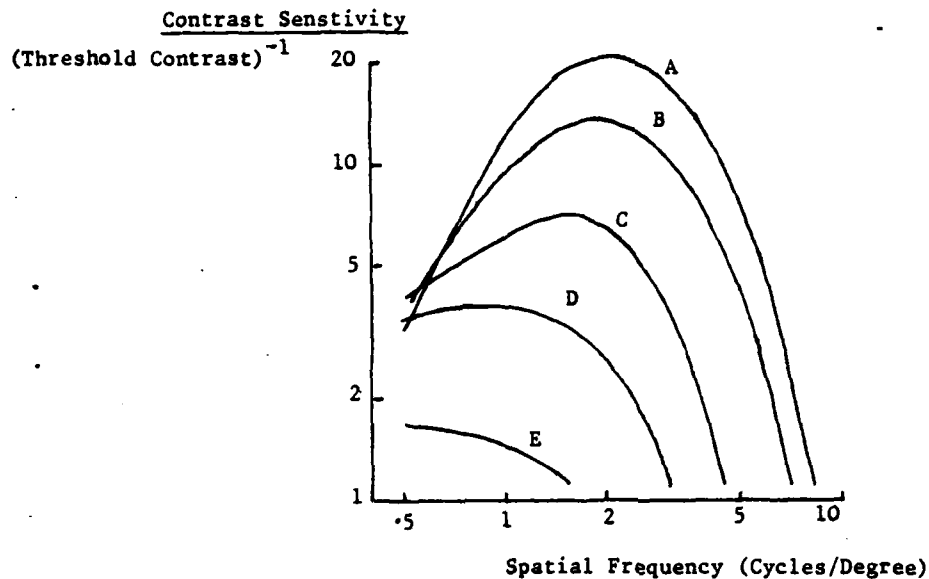


FIG.6 - Contrast Sensitivity of the peripheral retina at varying luminances and spatial frequencies (after Ditch and Green).

The target measured $8^\circ \times 3^\circ$ and was located 12° in the temporal retina.
 Contrast was defined by $\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$

The target produced a mean retinal illumination of:

- A) 1.5 log trolands
- B) 0.5 "
- C) -0.5 "
- D) -1.5 "
- E) -2.5 "

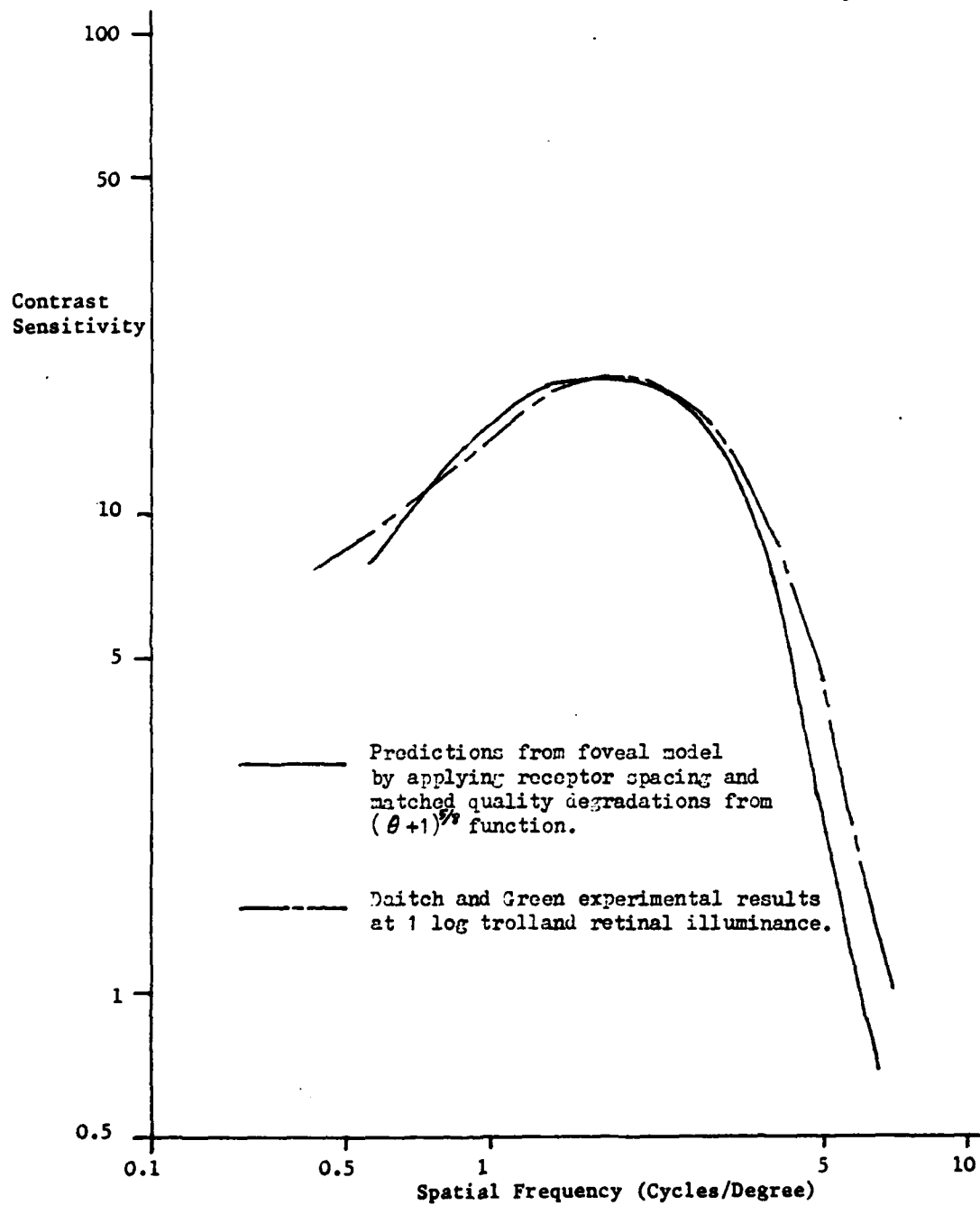


FIG.7 - Peripheral Contrast Sensitivity at 12° from Fovea

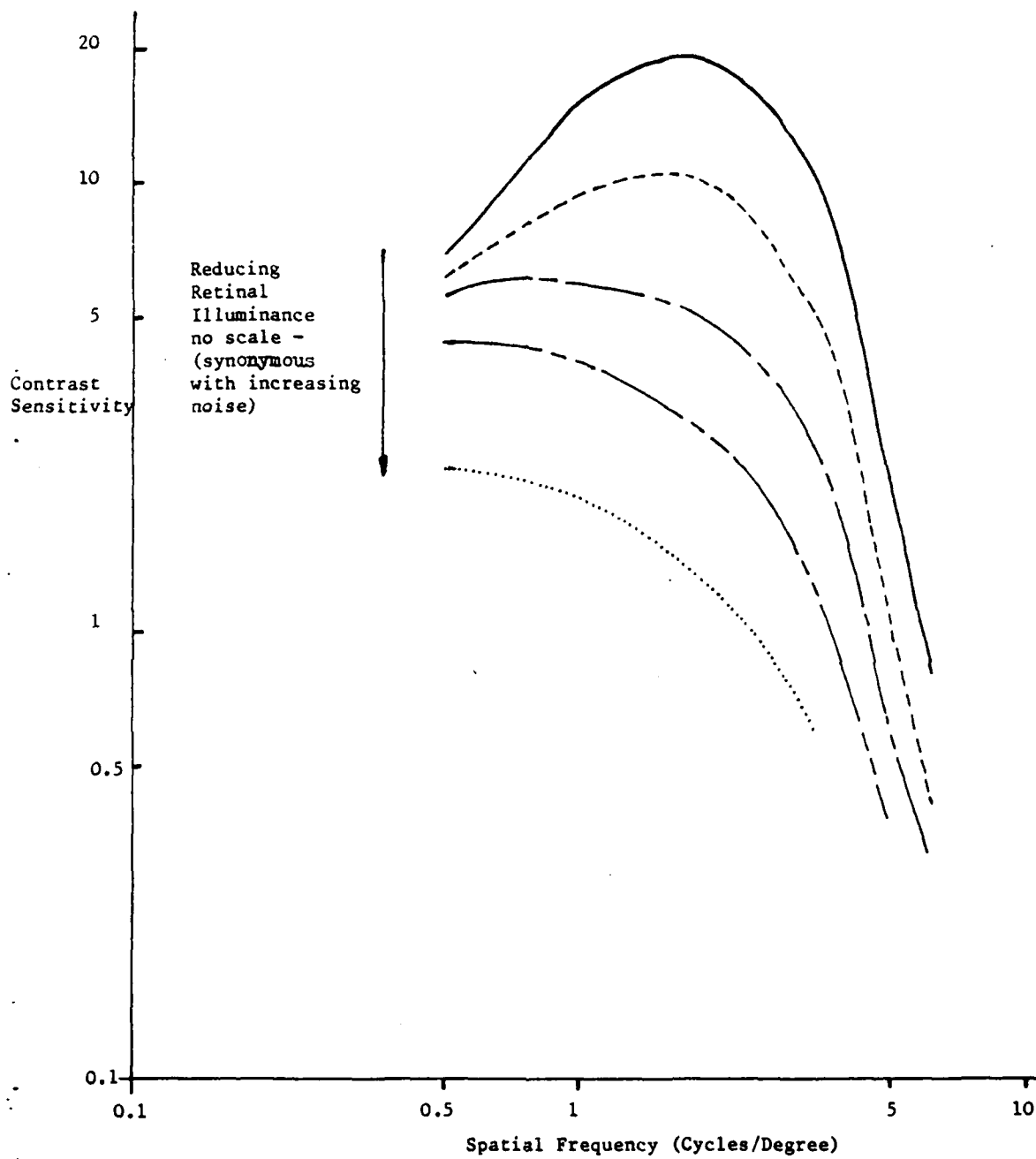


FIG.8 - Peripheral Contrast Sensitivity Predictions - 12° off fovea.
Effect of Retinal Illuminations.

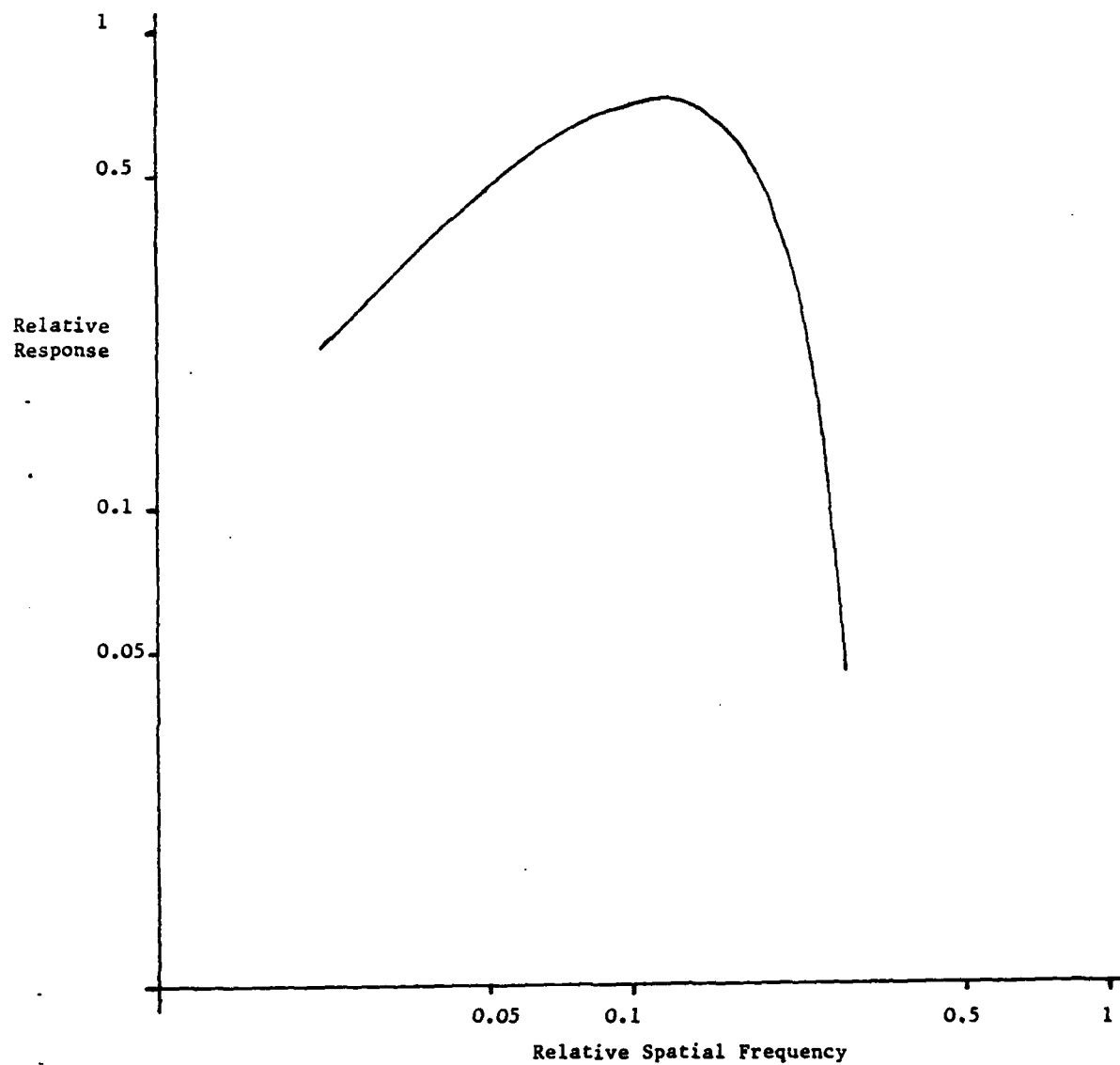


FIG.9 - The Retinal/Neural Contrast Sensitivity Function based on simple Integration Areas and Sampling.

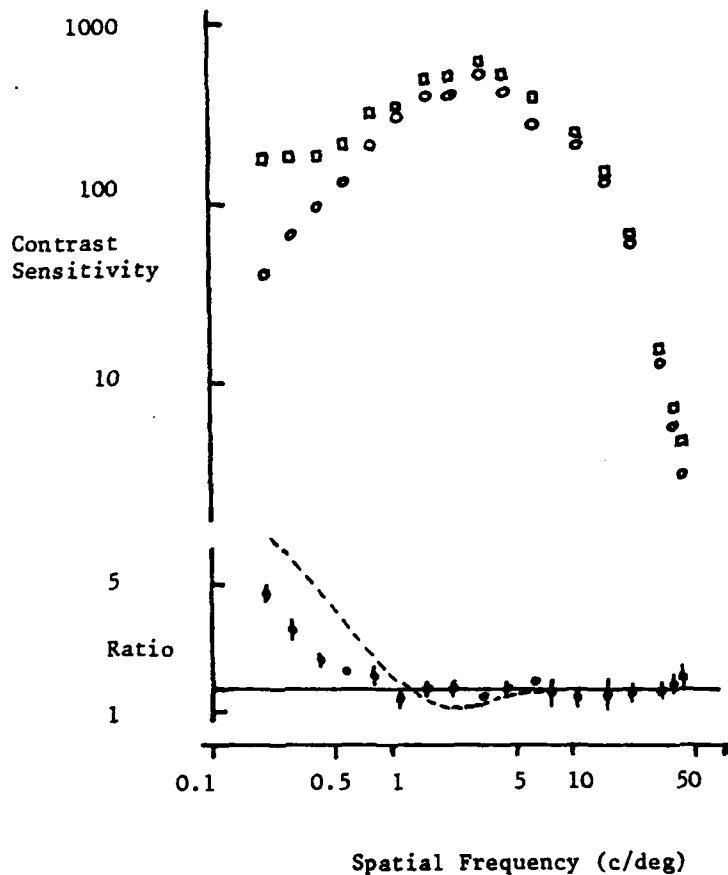


Fig 10

Contrast Sensitivity for Sine-Wave Gratings (O) is compared with that for Square-Wave Gratings (□) at a luminance of 500 cd/m². The ratio of the contrast sensitivities at each spatial frequency is plotted at the bottom of the figure (the bars show \pm S.E. of mean). A continuous line is drawn through the ratios at $4/\pi = 1.273$. The dashed line indicates the predicted ratio assuming a simple peak detector mechanism (from Campbell & Robson).

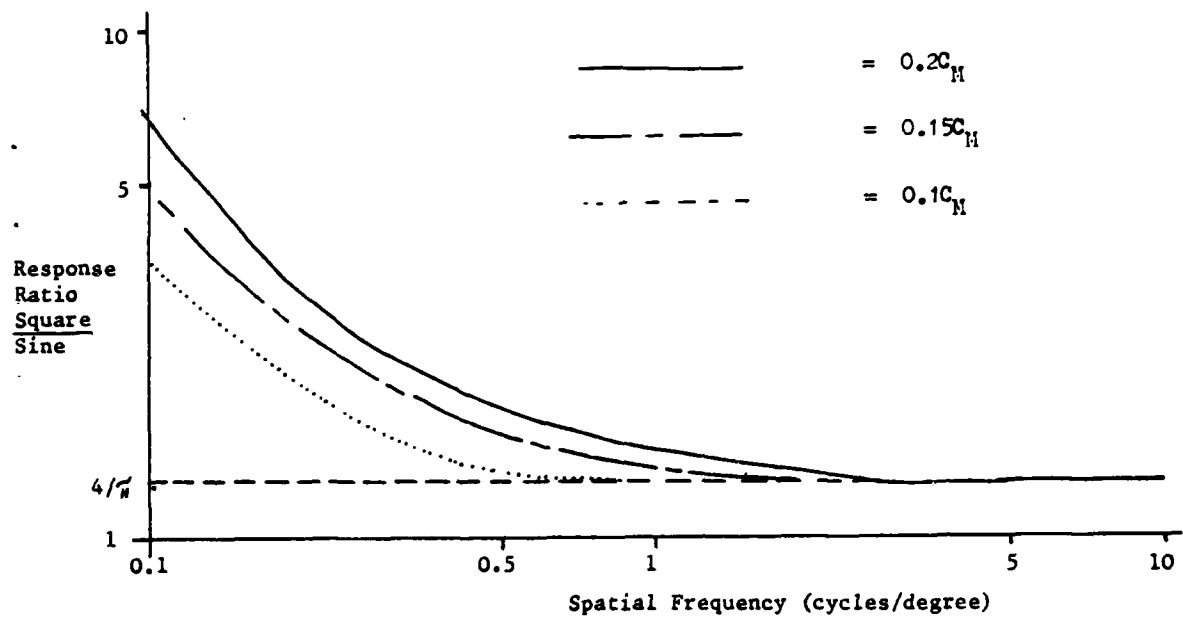


FIG.11 - Ratios of Square Wave to Sine Wave Response at approximately 1 Degree from Fovea.
 (For other retinal positions the curves should be shifted horizontally approximately in accordance with local quality factors)

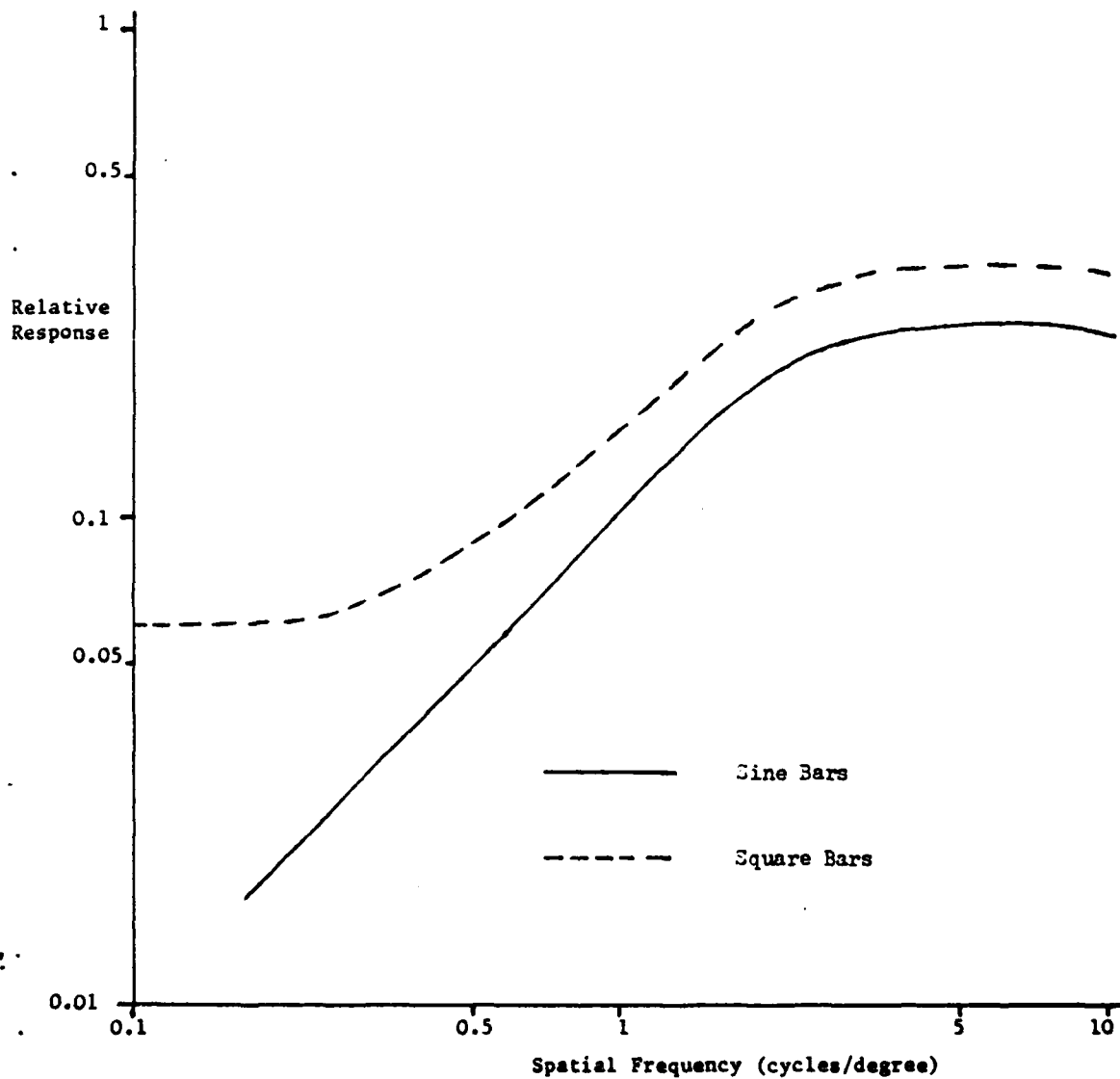
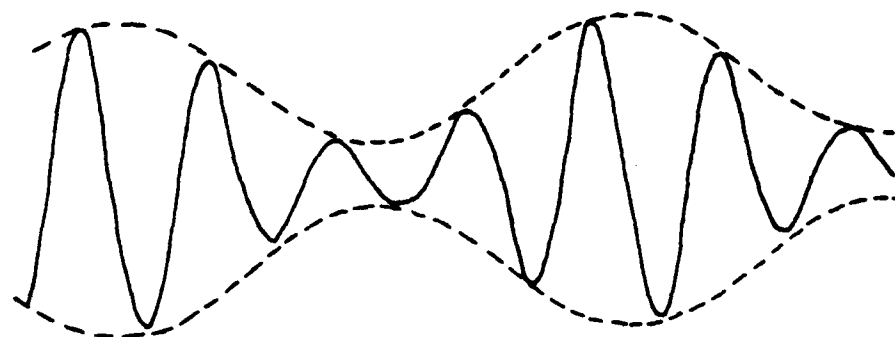


FIG.12 - Comparison of Contrast Sensitivity Functions for Square and Sine Bar Patterns (assuming a Noise σ of $0.2 C_M$)



————— 'Carrier' frequency $\frac{(f + f')}{2}$

----- 'Beat' frequency $\frac{(f - f')}{2}$

Fig 13

The Resultant Modulation from Retinal Superposition of Two Sinusoidal Fringes of Similar Spatial Frequencies.

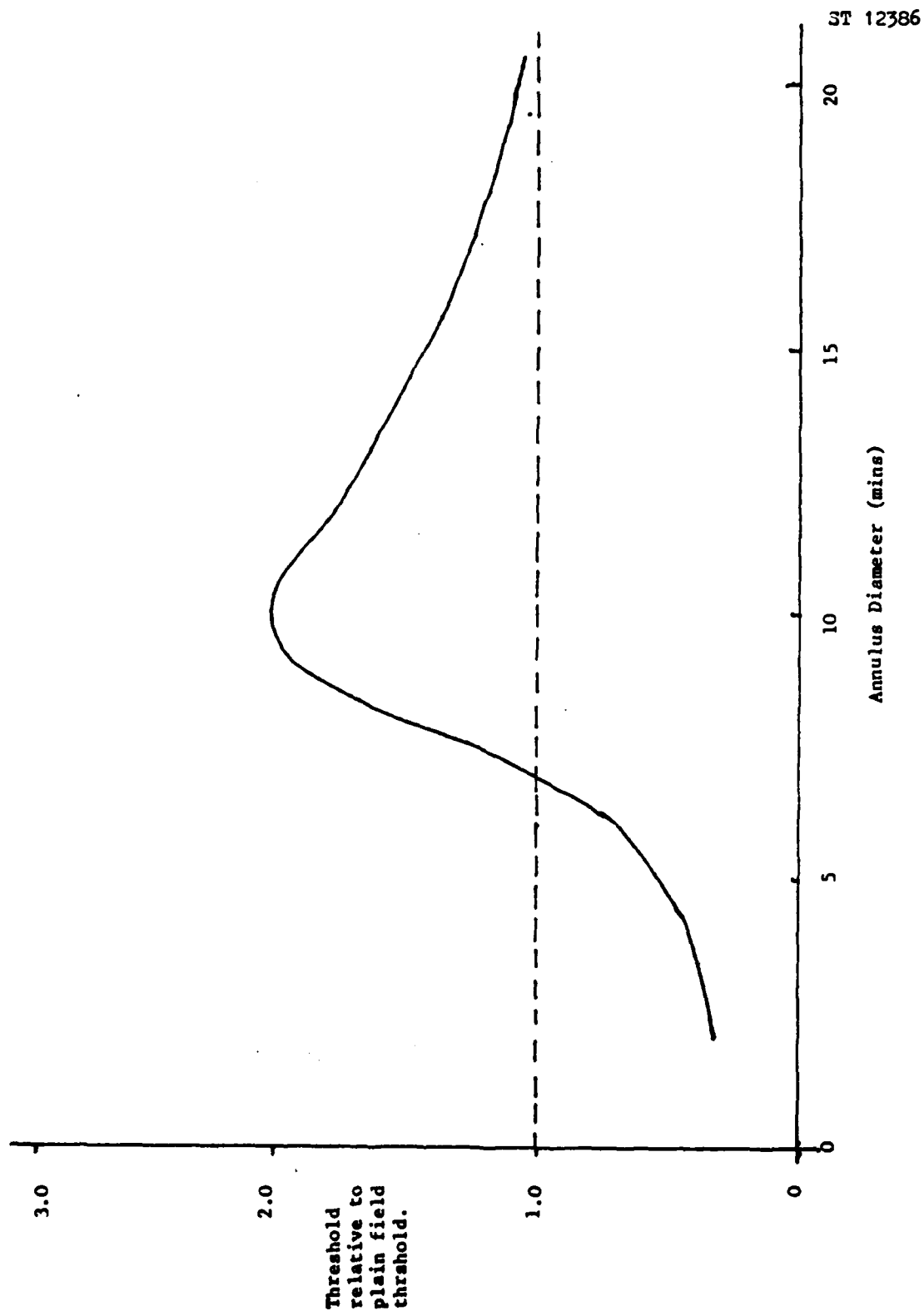


Fig 14 - Threshold Trend for a Small Disc Stimulus as a Function of Diameter of a Sub-threshold Annulus of Constant Area 9 sq mins.

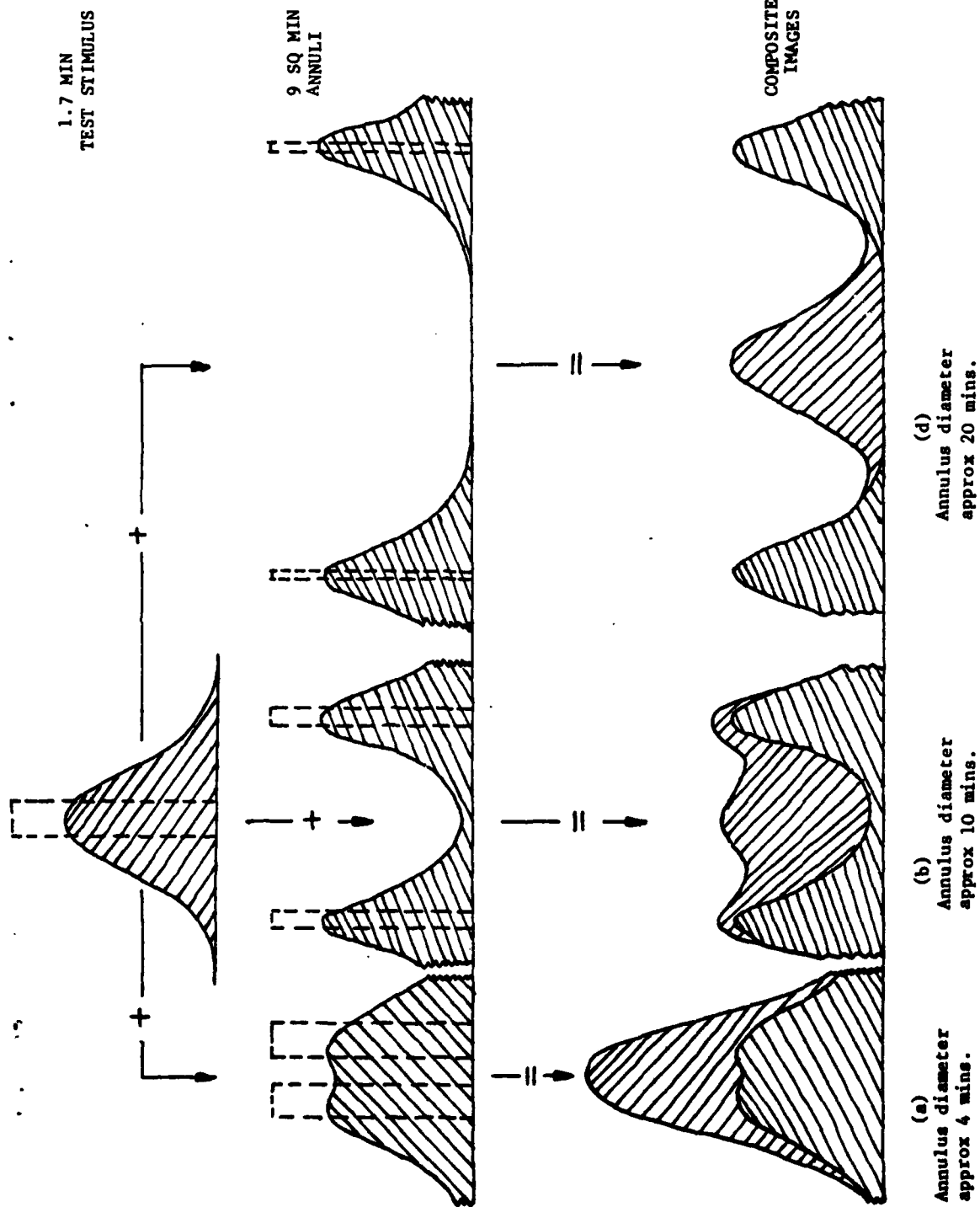


Fig 15 - Retinal Image Profiles for Presentation of a Small Disk Stimulus in the Presence of Various Sub-threshold 9 sq. min Annuli.

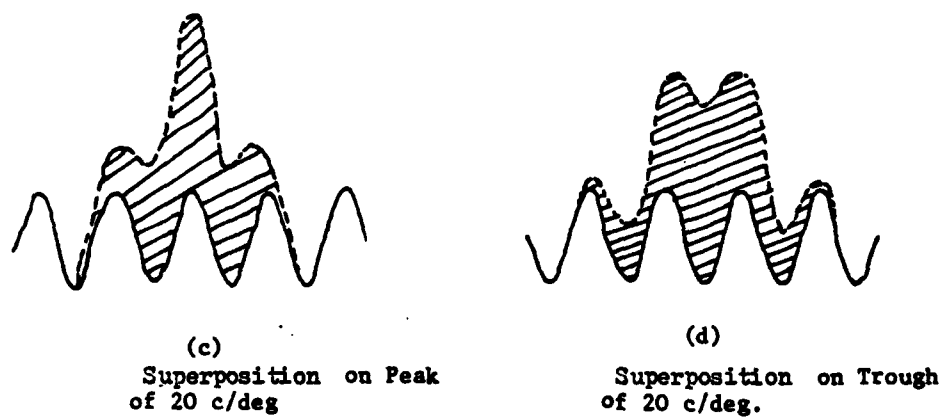
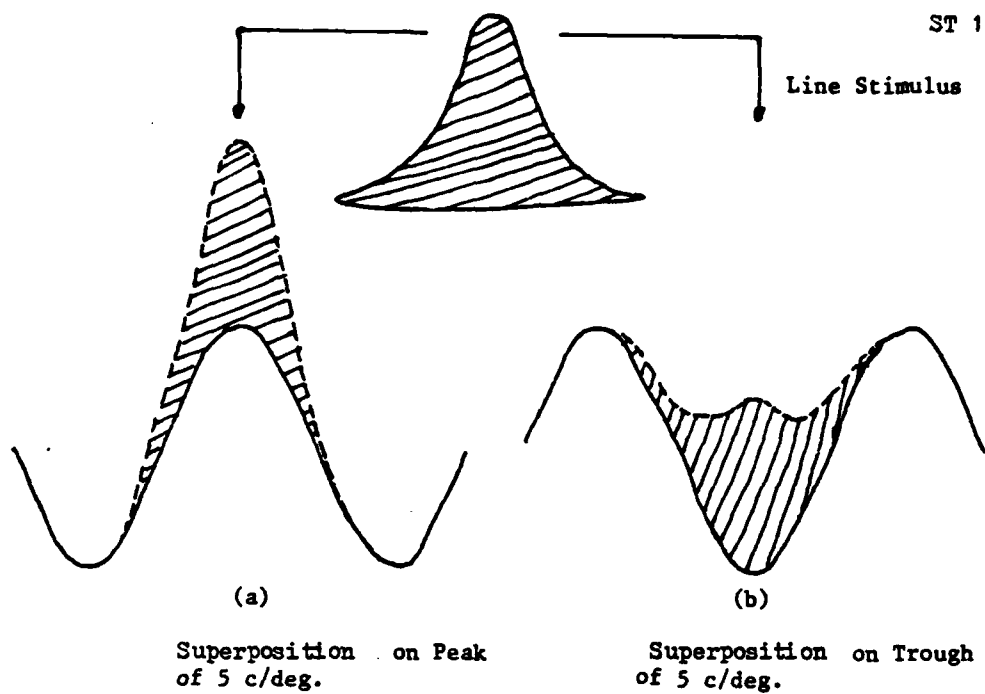


Fig 16-

Retinal Images for Superposition of Line Stimulus on Sub-threshold Sinusoidal Patterns.

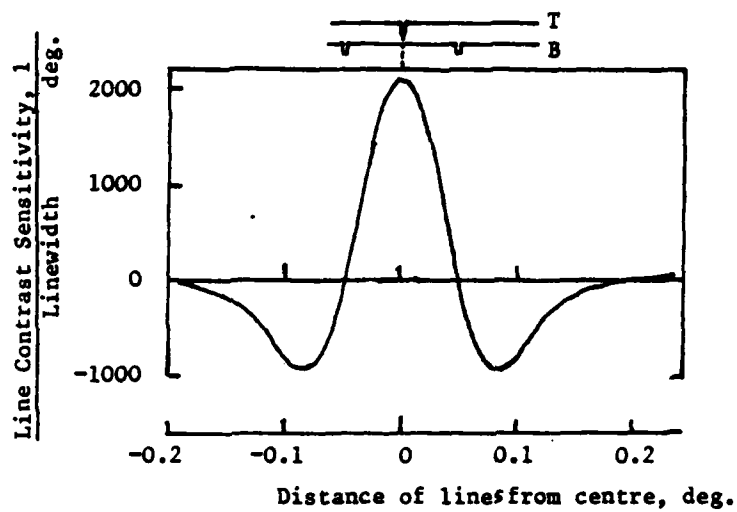


FIG.17 -

Line threshold sensitivity as a function of spacing of a pair of adjacent sub-threshold lines as measured by Kulikowsky and King-Smith.

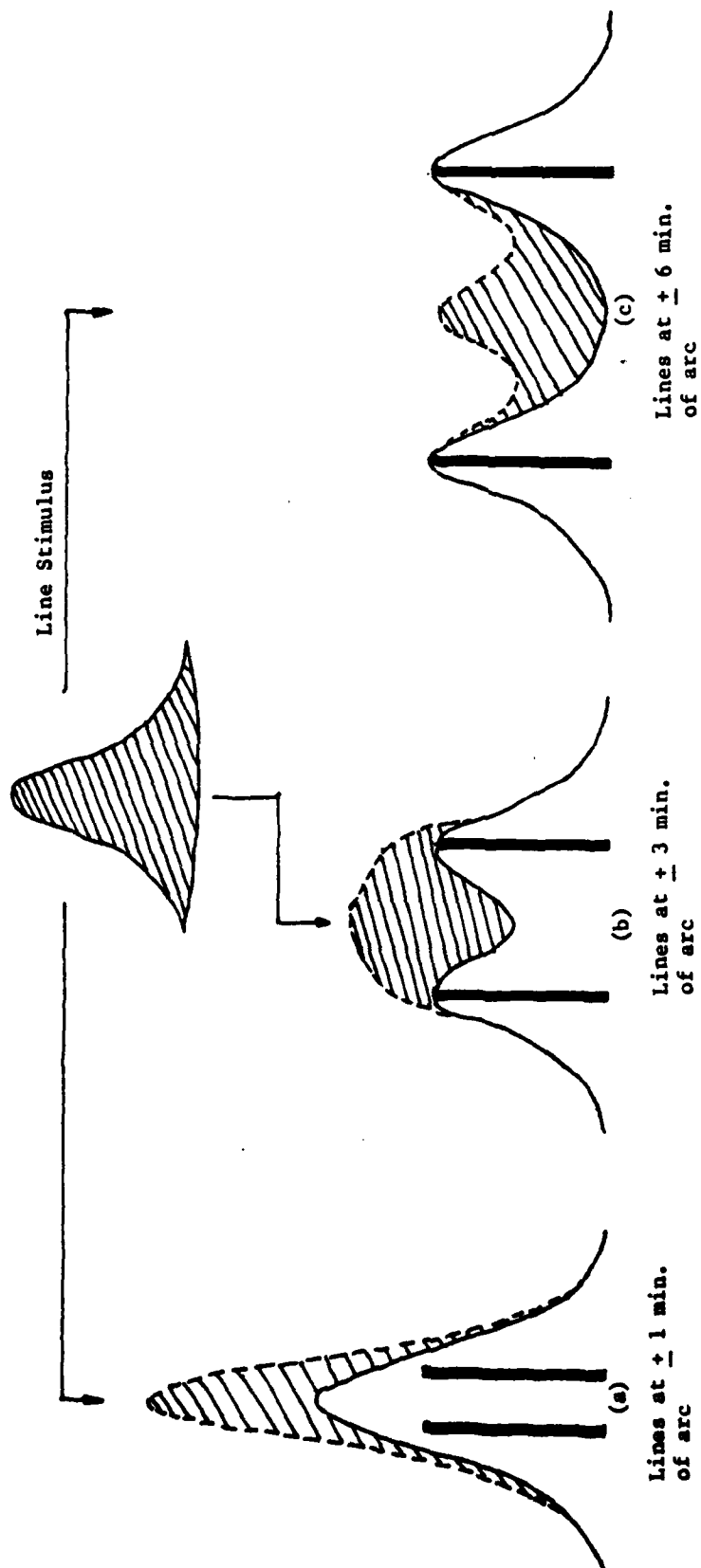


FIG.18 - Retinal Images due to Superposition of a Fine Line on Pairs of Fine Lines.

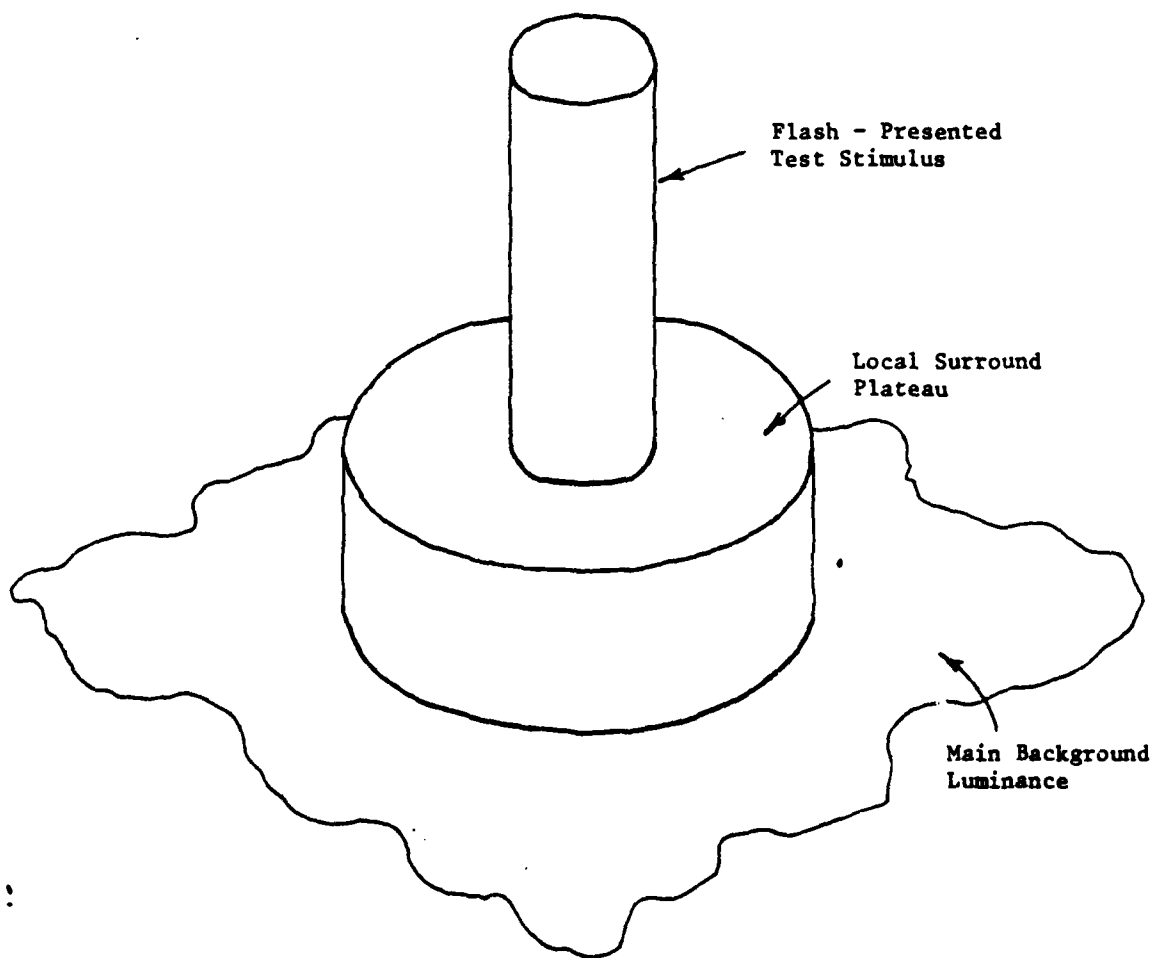


Fig 19

The Form of Stimulus Presentation Situation Studied by Westheimer and by Enoch et. al.

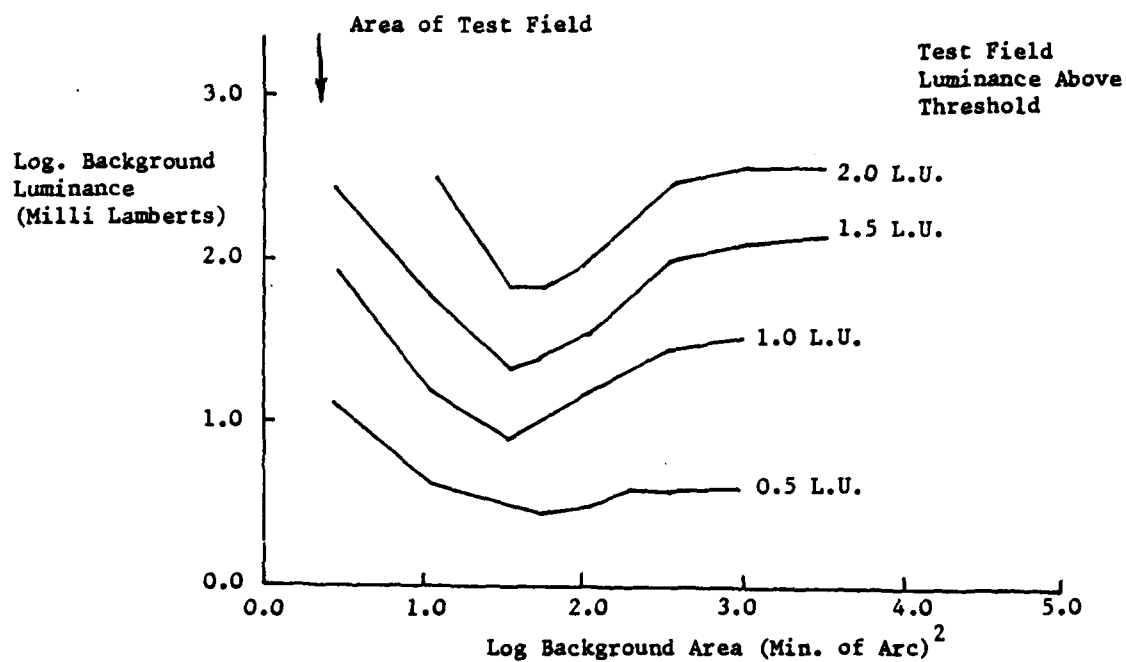


FIG.20 -

The log local background luminance necessary to make a flashing test field just disappear as a function of local background size. Flash duration 14msec. Data are means of 3 observers (from Enoch et al).

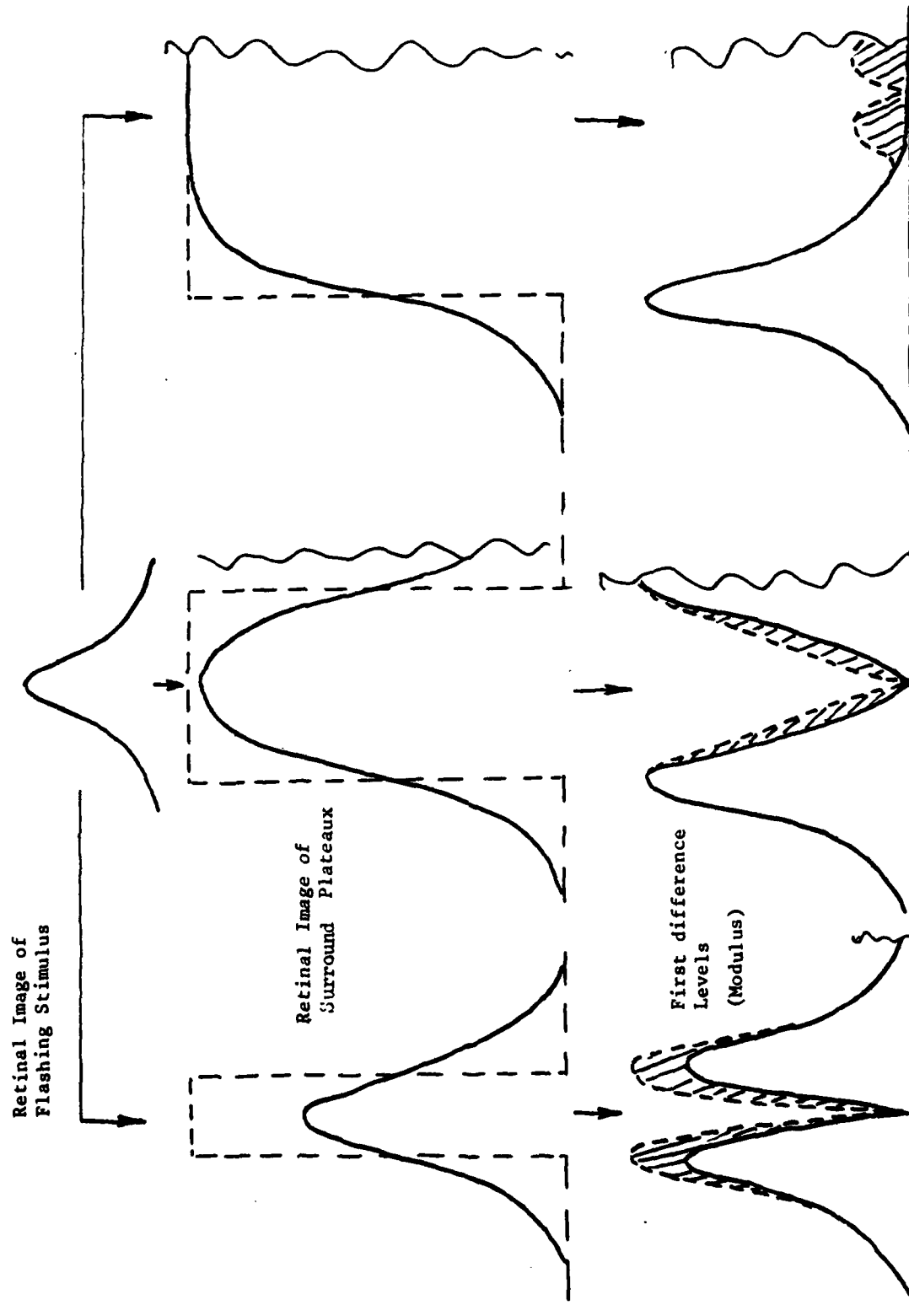


Fig 21

Representation of Retinal and Post Retinal Effect for Enoch et al's Receptive Field Studies.

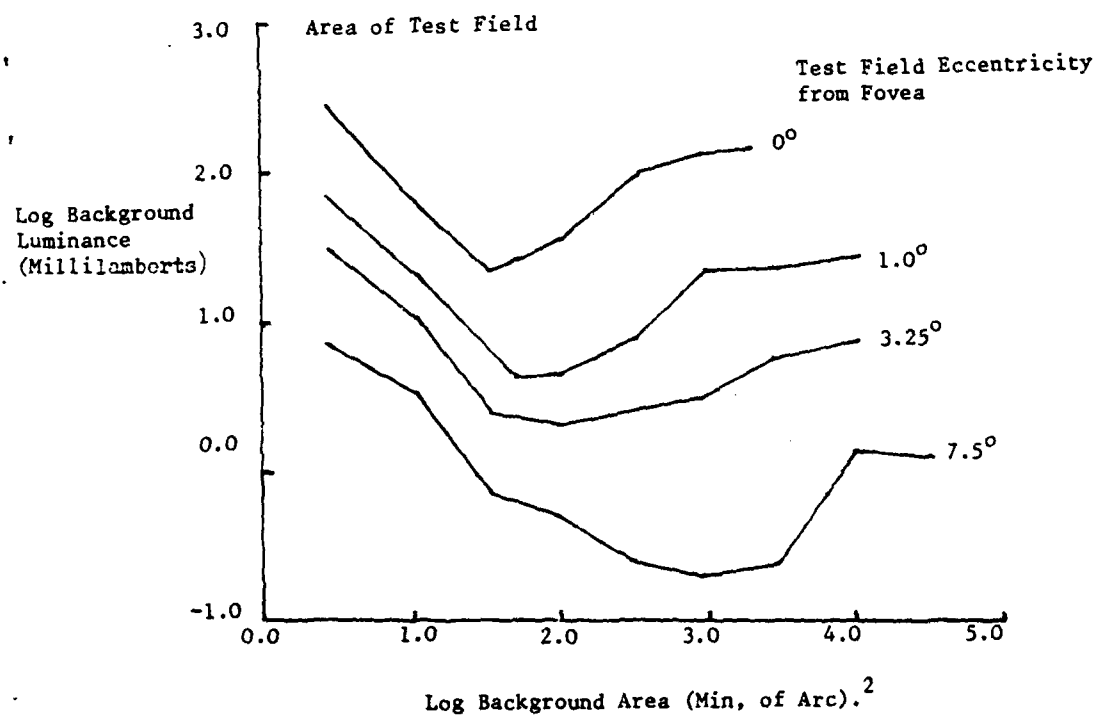


Fig 22

Log local background luminance necessary to make a flashing test field just disappear as a function of retinal location and local background area. Test field luminance always set at 1.5 L.U. above absolute photopic threshold. Test flash duration 14 msec.

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B.A.C. STEVENAGE

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Mr. R.A. Holloway
Mr. B. Davies
Mr. H. Yee
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Mr. G. Hawkins

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Mr. F.I. Reynolds

D.O.A.E

Mr. G.P. Owen

R.A.R.D.E

Dr. N.D. Haig
AP2 Branch.

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